Haystack Observatory – Small Radio Telescope Lab Exercises

Measure System Temperature Using Vane Calibration

Introduction:
The user should calibrate the telescope before making any observations. The SRT uses an ambient-temperature vane calibrator to obtain a measure of the system noise, background sky, atmosphere and spillover from the feed. The vane is a square-ish piece of absorber material attached to an arm that can allow the absorber to completely cover the feed aperture during the calibration sequence. The calibration is the ratio of the power measurement by the receiver with the vane enabled and blocking the feed divided by the power measurement by the receiver when the vane is retracted and the signal is received from the sky (this includes contributions from spillover). The power ratio is given in the equation below:

$P_{vane} / P_{sky} = (T_{sys} + T_{vane}) / (T_{sys} + T_{spillover} + T_{sky})$

Where

P_{vane} = the power measurement with the vane deployed,
P_{sky} = the power measurement with the vane retracted,
T_{vane} = the ambient temperature of the vane,
$T_{spillover}$ = the feed spill-over
T_{sky} = the combined temperature contributions from the sky and
T_{sys} = the system temperature (in this case, effectively the receiver temperature)

The minimum signal power that can be distinguished from the random fluctuations in the output of a measuring system caused by noise inherent in the system is the sensitivity of the system. If the system noise has a power, P watts, then the equivalent system temperature or noise temperature can be described by

$T = P/kB$

Where

K = Boltzman's constant (1.38×10^{-23} W Hz^{-1} K^{-1}),
B = the bandwidth and
P = power in watts
(Note: this is just the Johnson-Nyquist Noise theorem that we discussed in class)

Procedure:
Before starting the SRT software, measure or look up the ambient temperature and enter it into the srt.cat file. To calibrate the system, move the telescope to an area in the sky that is close in elevation and approximately two beamwidths (about 10 degrees) offset in azimuth from the source that is to be observed. If the sun is being observed, the azimuth offset should be larger, perhaps 40 degrees. The SRT user can manually calibrate the system using a left mouse-button click on the Cal button on the command tool bar at the top of the SRT console window.

After the approximately 20 second calibration routine, the resulting calculated system-noise-temperature, T_{sys} will be printed in the information side bar. Approximately 20 degrees of the total system temperature reported will be accounted for as the receiver temperature T_{rec}. Record the system temperature, the time of your observation, and the ambient temperature. After the calibration step (which will also flatten the bandpass), double-check the automated calibration by measuring the power received on blank sky compared with that received from the absorber. Use the Y factor calibration we discussed in class to calculate the system temperature, and compare with the temperature derived by the automated routine.

Writeup:
Describe the calibration procedure and record the system temperature that you measure along with the time at which you measured it. Collect data from the other observing groups and make two plots: (1) system temperature as a function of time throughout the day, and (2) system temperature as a function of ambient temperature. By how much does the system temperature fluctuate throughout the day? Does it seem to track the ambient temperature? How does the system temperature compare to the theoretical quantum limit on the receiver temperature for this system?

Measure Antenna Beamwidth using the Sun as a Signal Source

Introduction:
The beamwidth of a radio telescope is the solid-angle measure of the half-power point of the main lobe of the antenna pattern. The half-power beamwidth (HPBW) can be measured by moving the telescope in a continuous scan across a very bright radio source. Except for the possibility of Cygnus-X or certain geosynchronous satellites, the only source available to the SRT is the Sun. Measurement of the beam pattern can help the user discover problems with optical alignment or aid in the determination of the antenna focus.

Procedure:
First, point the SRT directly at the Sun. You may want to scan around the Az/El position given by the SRT software to make sure that you are actually centered on the position of the Sun (the offsets seem to vary somewhat over time). Next, scan across the Sun in both azimuth and elevation in 1-degree increments, making sure to begin and end your measurements far enough away from the Sun that it does not contribute to the antenna temperature.

Writeup:
Generate two plots of antenna temperature as a function of degrees offset in (1) azimuth and (2) elevation. Measure the HPBW of the SRT antenna in both azimuth and elevation. Are they the same? Why or why not? (Hint: Since the Sun is unlikely to be near the horizon, you will need to be careful with the azimuth axis. Try to figure out the appropriate correction factor to apply, since circles of constant elevation are not great circles.)

How does your plot of the gain pattern of the antenna compare with what you would expect for a uniform circular aperture (2.4m in diameter, observing at a wavelength of 21cm)? Plot an Airy function over your data (you will need to add a vertical offset to account for the system temperature). How does the beamwidth you measured compare with the theoretical expectation? Do you see the sidelobe levels you expected to see?

One reason your data will not match the theoretical expectation is that the aperture is undergoing nonuniform illumination (another reason is that the feed may be slightly out of focus). The tapered illumination caused by the beam pattern of the feed can be well approximated by the following function:
$\varepsilon(\rho) = [1 - (2\rho/D)^2]^\gamma$,
Which results in a gain pattern
$G(\theta) = [2^{\gamma+1} (\gamma+1)!]^2 (4\pi A_g / \lambda^2) [J_{\gamma+1}(\pi D\theta/\lambda)/(\pi D\theta/\lambda)]^2$
For most real-life feeds, $\gamma \sim 1$. Try plotting the gain pattern for γ=1, and see if it provides any improvement over the Airy pattern expected for the uniform illumination condition.

Measure Aperture Efficiency

Introduction:
Aperture efficiency, η, is the ratio of the effective aperture of a radio telescope divided by the true aperture. True aperture A_g, is defined as the collecting area of the telescope surface. Effective aperture A_e, can be understood as the losses from a perfect reflector due to such things as blockage of the surface by the feed and feed supports, over/under-illumination of the surface by the feed and other factors such as surface irregularities. Typically, total losses amount to 35%-50% of the theoretical limit. That is, 50%-65% of the power from the observed source reaches the receiver.
$\eta = A_e/A_g$
For the purposes of the use of the SRT, the aperture efficiency (η) is expressed by the following equation:
$\eta = 2kT_A/FA_g$
where
T_A = the antenna temperature in degrees K,
k = Boltzmann constant (1.38×10^{-23} W Hz^{-1} K^{-1}),
F = the radio source flux density (1 Jy = 10^{-26} W m^{-2} Hz^{-1}) and
A = the area of the reflector in m^2
Measurement of the aperture efficiency of the SRT can be carried out on several sources: Cygnus-X, Cas-A, the Moon and even the Sun. The procedure below will use Cas-A, which has a flux density of 2000 Jy at a wavelength of 1420 MHz.

Procedure:
You may need to come back on your own time when Cassiopeia is high above the horizon. The ambient temperature will have changed, so be sure to enter the new temperature into the srt.cat file. Since this is a "continuum" measurement, and because Cas A is located close to the galactic plane, the frequency setting for the receiver must be away from the 1420.4 MHz hydrogen line (e.g., freq 1419 20 0 for frequency, number of samples, and sample spacing). Then, move the telescope to an area of the sky near the source to be observed, and perform a calibration using the “Cal” button on top of the SRT user interface (as in the first part of the lab above). You will also want to make your own measurement of the system temperature. Since system temperature can vary with altitude

due to changing amounts of atmosphere and pickup from the ground, the calibration should typically be done at the same elevation as the source but offset in azimuth by at least two beamwidths (~15 degrees for a 2.4m dish, or a bit more if you're at high elevation). Use the offsets you measured when you were observing the Sun to make sure you are pointed at the correct position.

You will need to perform observations using the beamswitching method. Beamswitching involves alternate on-source/off-source observations with each off-source observation alternating in a plus/minus azimuth direction. Record a few (3-5) values of antenna temperature on the source, then move off the source and record a few more values of antenna temperature. Repeat at least 10 times, making sure to spend no more than a few seconds at each position (in case the gain changes rapidly).

Discussion of Data Reduction:

The resulting data output file will be a succession of on-source then off-source samples. The statistical reduction to arrive at an average Antenna Temperature T_{ant} to use in the above Aperture Efficiency equation is as follows:

$P_k = P_{on} - P_{off}$

Where

k = the cycle number. (On/Off pair)

For, k = 0,2,4 $-P_{off}$ + previous P_{on}

For, k = 1,3,5 P_{on} - previous P_{off}

For N cycles

$P_{ave} = \Sigma P_k / N$

Where P_{ave} = average of N on/off pairs

$P_{SD} = (\Sigma P_k^2 - N P_{ave}^2)^{1/2} (N - 1)^{-1/2}$ For N>1

Writeup:

Calculate the aperture efficiency of the SRT, making sure to properly account for the system temperature.

Look up the angular diameter of the Sun (cite your source) and use it along with your previous measurements of antenna temperature and aperture efficiency to estimate the flux density of the Sun at a wavelength of 21 cm. Collect your classmates' measurements and plot the Solar flux as a function of time throughout the day (we might see a flare!). Estimate the uncertainty on your measurement. Compare your measurement with the official NOAA record of Solar flux, which you can find on this web page: http://www.swpc.noaa.gov/ftpdir/lists/radio/7day_rad.txt

(Note: you will need to look up the Solar flux within 7 days of when you performed the experiment!) Using the NOAA records, estimate the spectral index of the Solar radiation. Is the spectrum thermal or nonthermal?

Radio Telescope Cheat Sheet

Basic Safety:

- There should ALWAYS be slack in the cables! Do not rotate the telescope to the point that the cables become taut.

- Keep the receiver unplugged when not in use.

- If conditions are very icy or very windy, do not operate the telescope. If at any time the telescope does not move easily, shut it down and email Prof. Hughes: amhughes@wesleyan.edu.

- Do not operate the radio telescope in the rain (a light cover of dew or drizzle on an otherwise clear day is fine, but you will not be able to make observations during precipitation anyway).

- If you encounter any problems with the radio telescope equipment, email Prof. Hughes. In case of a telescope-related emergency (mutant squirrels chewed through power cables, etc.), call Roy Kilgard: 860-597-0551.

Setting Up:

1. Make sure the power strip is turned on.

2. Hit the power button on the Linux machine and turn on the monitor. Log in with username amhughes and password vanvleck

3. Turn on the power switch on the back of the rotor control box. When it is on, the numbers giving altitude and azimuth should be illuminated in green on the front of the box.

4. Plug the receiver in to the power strip.

5. After you log into the Linux machine, open a terminal and cd to the srtn directory on the desktop ("cd Desktop/srtn").Type "./srtn" to start the SRT software.

Taking Data:

1. Calibrate the telescope. Check the SRT software display to see the location of the galaxy and any other bright radio sources. Move to a blank position on the sky, at least 40° away from the galaxy and at least 30° above the horizon. Just below the north celestial pole is usually a good bet. Click the "calibrate" button at the top of

the SRT control software GUI. It will say tell you to place the absorber and press enter. You have two options. Either slew the telescope to the biggest, bushiest tree you can see on the horizon and press enter, or (preferred) hold the "absorber-on-a-stick" in front of the feed and press enter.

2. Slew to your target. Until the authors release new software allowing the SRT system to interface with the new controller that we use to move the telescope, we need to look up the coordinates on the display and use the following formula to account for offsets and flipping of the alt and az displays. If the true altitude and azimuth are alt_{true} and az_{true}, then the altitude and azimuth you should enter into the control box are:

   $$alt = alt_{true}$$

   $$az = 180^{\circ} - az_{true}$$

3. Integrate. Once you are on source, hit the "clear" button at the top of the SRT control software GUI, and wait. As time passes, you will see the integrated spectrum appear in the frame at the center right of the GUI. Don't forget to save your data and store it on a flash drive. If you are only interested in total power (e.g., for the part of the lab that involves determining the beamwidth by scanning across the Sun), read the power level from underneath the middle of the three spectral frames in the GUI. No need to integrate to build up signal.

Shutting Down:

1. Close the SRT control software by pressing the "Stow" button, followed by the "Exit" button.

2. Shut down the Linux machine and turn off the monitor.

3. Slew the telescope back to its home position (so that the display on the control box reads 0° altitude and 0° azimuth), making sure to undo any wraps in the cable that occurred during your observations.

4. Turn off the switch on the back of the controller box.

5. UNPLUG THE RECEIVER.